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Ventilation Measurements at Underground Mine Regulators

U.S. Department of Labor
Mine Safety and Health Administration

Informational Report
IR 1128
1981

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Ventilation Measurements at Underground Mine Regulators

U.S. Department of Labor
Ray Marshall, Secretary

Mine Safety and Health Administration
Robert B. Lagather, Assistant Secretary
1981

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VENTILATION MEASUREMENTS AT UNDERGROUND MINE REGULATORS

by

Robert L. Smith [1] and Robert A. Haney [1]

ABSTRACT

The Mine Safety and Health Administration conducted two studies to investigate practical and accurate methods for computing the air volumes passing through underground mine regulators and rectangular openings in stoppings. The first series of tests produced a revised regulator formula using the static pressure drop at the regulator and the area of the opening to calculate the volumetric flow through the regulator. An overall discharge coefficient was determined experimentally for all pressure losses at regulators. The second set of observations used 4-inch rotating vane anemometers to develop methods factors for velocity readings at underground regulators. Methods factors were determined by comparing the corrected measured velocity at the centerline of the openings with the average air velocity passing through the regulators. Methods factors were dependent on the size of the opening, the location of the reading (inlet or discharge side of the regulator), and the type of instrument support (rod-mounted or hand-held); they showed little dependence on the air velocity.

INTRODUCTION

Air quantities must be determined at various locations underground as a part of routine inspection practices and normal mine operation. While hand-held centerline anemometer readings may be valuable in determining day-to-day ventilation variations, their reliability for an accurate evaluation of a mine ventilation network has not been determined. Split-area traversing techniques by vane anemometer or timed smoke-cloud travel are frequently required to measure the air quantities accurately. Either technique may be time consuming when performed properly.

Underground mine ventilation networks use regulators to proportion the air distribution so that the desired quantities flow to all areas of the mine. A regulator takes the form of an orifice (9, 11)[2] that constricts an air

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[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

stream to create a pressure drop (8). The actual pressure drop at the regulator opening closely approaches the total pressure drop induced on the airstream. Regulators, usually constructed with concrete blocks, can be built in airways or formed by removing blocks from a stopping. The regulator opening often has a sliding door that adjusts to vary the size of the opening.

Regulators or rectangular openings in stoppings offer a potentially good air quantity measuring location because of the ease with which the area, velocity, and static pressure drop can be measured; however, due to changes in airflow configuration at regulators, such measurements are generally considered unreliable. Although these localized airflow changes do exist, proper evaluation can determine their effects on air velocity and air quantity measurements.

Two methods may be considered for determining the air quantity passing through a regulator. The first employs the static pressure drop across the regulator and the classic regulator formula used by mine ventilation specialists and engineers for over 75 years:

$$A = \frac{40\ Q}{\sqrt{H}} = \frac{q}{2500\ \sqrt{H}}\ , \qquad (1)$$

where A = cross-sectional area of regulator opening (square feet),
Q = air quantity through regulator (cubic feet per minute in units of 100,000),
q = air quantity through regulator (cubic feet per minute),
and H = static pressure drop across regulator (inches water gage).

Examination of the derivation of the regulator formula (2, 6, 9, 11) shows equation 1 to be based on two assumptions: a 100 percent conversion of velocity pressure to static pressure and a coefficient of contraction[3] of 65 percent. Incorporating these assumptions yields the equation:

$$A = \frac{38.5\ Q}{\sqrt{H}} = \frac{q}{2600\ \sqrt{H}} = \frac{q}{4000\ X\ 0.65\ \sqrt{H}}\ . \qquad (2)$$

So it was decided that it would be beneficial to determine the proper equation for a regulator experimentally rather than rely on the derived formula. Data measured at an orifice would permit an overall discharge coefficient to be resolved from which the true air quantity could be calculated (8). The overall discharge coefficient is the ratio between the true and theoretical discharge and combines the effects of all the energy losses produced at the regulator.

---

[3]The coefficient of contraction is the ratio between the area of the orifice and the minimum cross-sectional area that occurs downstream where the airflow streamlines contract. Past this point the streamlines expand to fill the mine entry again.

The second method for determining the air quantity uses an anemometer measurement. A study employing rotating vane anemometers to measure the velocity at the intake of an exhaust tubing installation demonstrated that by applying methods factors, the anemometer readings could be corrected to reflect the true velocity (5, 10). In another series of tests (3), rotating vane anemometer readings at the centerline of rectangular openings in stoppings were used to establish proper ventilation for smoke control in fireproof structures. Based on these studies, it was decided that methods factors could also be derived for rectangular openings.

TEST PROCEDURE

Testing was designed so that a comparison could be made between the true air quantity passing through the regulator and the anemometer measurement or the static pressure measurement. Tests were conducted in a horizontal wind tunnel approximately 700 feet in length (fig. 1). Airflow for the tests was induced by a 5-foot diameter axial flow fan. Inside the wind tunnel, two measuring stations were constructed. The first station, 128 feet from the

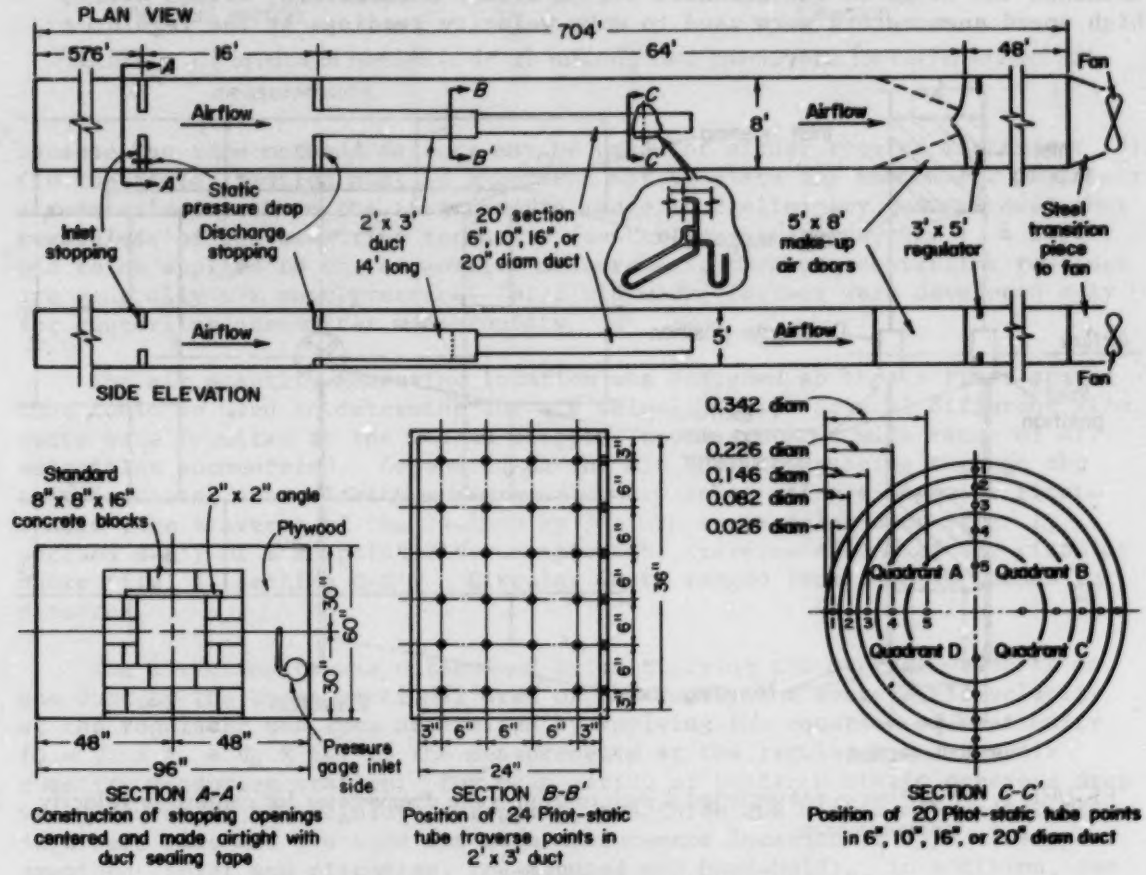

FIGURE 1. - Wind tunnel testing facilities.

fan, was the regulator where static pressure drops and rotating vane anemometer readings were taken. The second measuring station was 112 feet from the fan and contained the test section used to determine the actual air quantity.

The regulator was constructed with 8-inch by 8-inch by 16-inch concrete blocks. The opening sizes tested were based on multiples of single block and half-block dimensions. In all, eight opening sizes were evaluated ranging from 8 by 8 inches (0.41 square feet) to 44 by 44 inches (13.18 square feet). Six opening sizes were square, and the other two were rectangular with aspect ratios of 1 to 2 and 2 to 3. Air velocities for the tests ranged from 320 to 4,835 feet per minute through the regulator openings.

Rotating vane anemometer readings were taken at the centerline of the inlet side of the regulator, and, when possible, at the centerline of the discharge side of the regulator. Readings were made with the anemometer mounted on a rod (fig. 2) and with the anemometer hand-held (fig. 3). In each case, the anemometer was positioned so that the plane of the stopping approximately bisected the anemometer frame. Indicated anemometer readings were corrected by applying a calibration curve to each reading. Since velocities often exceeded the range of the standard 4-inch 8-vane anemometers, 4-inch 4-vane high speed anemometers were used to make velocity readings at the regulator

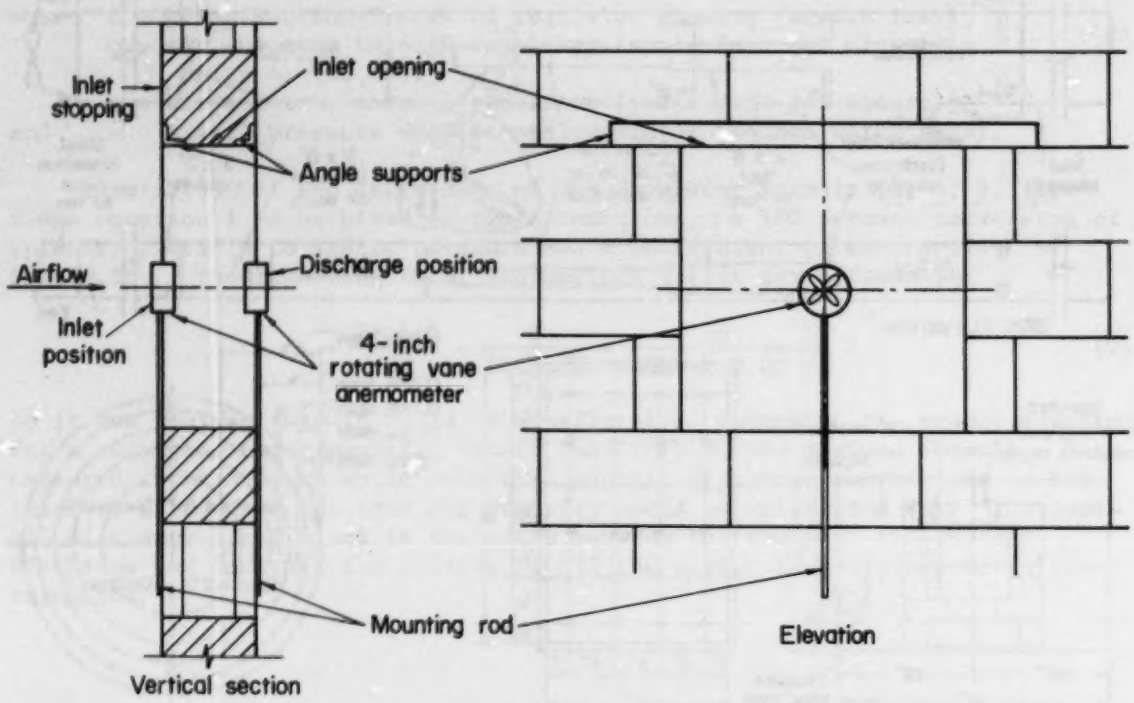

FIGURE 2. - Position of rod-mounted 4-inch rotating vane anemometer for centerline velocity measurements.

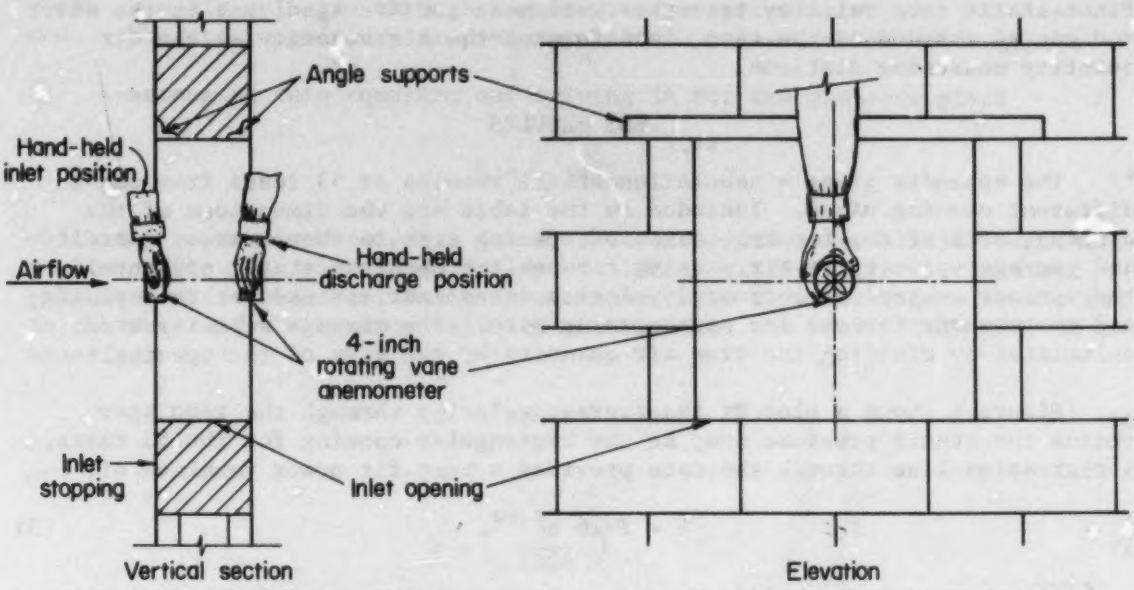

FIGURE 3. - Position of hand-held 4-inch rotating vane anemometer for centerline velocity measurements.

because the same methods factors may be used for either type of instrument (5). (In the field, caution must be exercised not to place any anemometer in an air-stream velocity above the instrument's range.) Preliminary tests showed that regardless of the measuring technique (centerline, traverse, etc.), a factor had to be applied to the anemometer measurement. Because centerline readings are generally the most practical for field work, factors were developed only for centerline anemometer measurements.

The air quantity measuring location was designed so that a Pitot-static tube could be used to determine the air velocity (1). Several different size ducts were required in the second stopping to measure the wide range of air velocities encountered. Depending on the air quantity passing through the test sections, air velocity measurements were taken using a 24-point Pitot-static tube traverse of the 24-inch by 36-inch rectangular duct (fig. 1, section B-B') or a 20-point Pitot-static tube traverse of one of the circular ducts (fig. 1, section C-C'). Circular ducts ranged from 6 to 20 inches in diameter.

The air quantity was determined by multiplying the average velocity in the duct by the cross-sectional area of the duct. The average air velocity at the regulator was then determined by applying the equation of continuity ($Q = V_1 \times A_1 = V_2 \times A_2$) to the measurements at the regulator and the air quantity measuring station. For each series of tests, a static pressure drop was measured at the regulator stopping, and three one minute anemometer readings were made and averaged for each measurement location or type of support examined (inlet and discharge, rod-mounted and hand-held). In addition, two

Pitot-static tube velocity traverses were made and averaged, one at the start and one at the end of the test, to determine the air velocity at the air quantity measuring stations.

TEST RESULTS

The appendix gives a tabulation of the results of 53 tests from eight different opening sizes. Included in the table are the dimensions of the opening, area of the opening, ratio of opening area to tunnel area, quantity and average velocity of air passing through the opening, static pressure drop, the various centerline corrected velocity determinations made at the opening, and the methods factors for each opening size. The average velocity was calculated by dividing the true air quantity by the area of the opening.

Figure 4 shows a plot of the average velocity through the regulator versus the static pressure drop at the rectangular opening for the 53 tests. A regression line through the data provides a best-fit power equation of:

$$V = 2916\ h^{0.52}, \qquad (3)$$

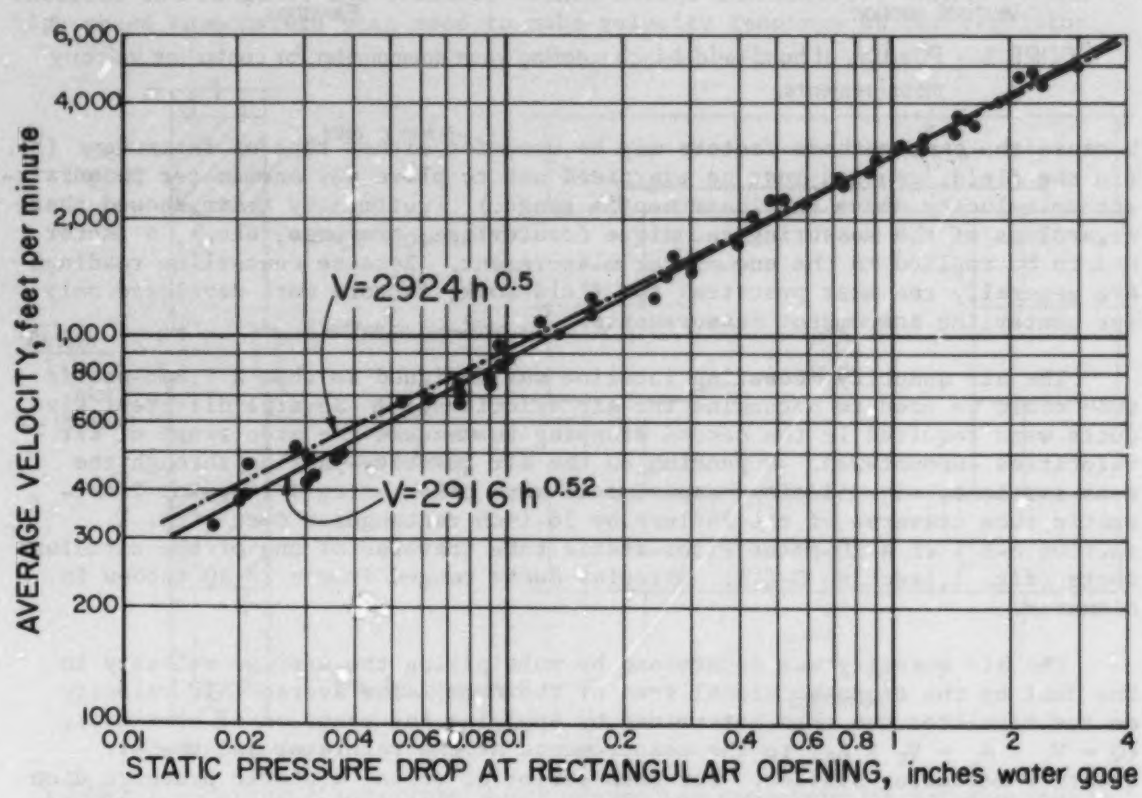

FIGURE 4. - Average velocity versus static pressure drop at rectangular opening for 53 tests.

where V = air velocity through regulator (feet per minute),
and h = static pressure drop at regulator opening (inches water gage).

Rearranging this equation and solving it for the pressure gives

$$h = \left(\frac{V}{2916}\right)^{1.92}, \tag{4}$$

which can be compared to other formulas developed to solve similar engineering problems (7). The exponential value of 1.92 is difficult to use in field calculations. Therefore, a second equation (also shown on figure 4) was fit to the data where a squared value of the exponent was used. This yielded the equation:

$$V = 2924\ h^{.5} = 2924\ \sqrt{h} \tag{5}$$

or

$$h = \left(\frac{V}{2924}\right)^{2}. \tag{6}$$

For pressure drops normally found at mine regulators, using equation 5 instead of equation 3 does not make any appreciable difference in the air velocity determination.

By multiplying both sides of equation 5 by the area of the opening and then solving for the area, a revised version of the regulator formula can be obtained:

$$VA = 2924\ A\ \sqrt{h} \tag{7}$$

$$q = 2924\ A\ \sqrt{h} \tag{8}$$

$$A = \frac{q}{2924\ \sqrt{h}} = \frac{q}{4005 \times 0.73\ \sqrt{h}} \tag{9}$$

$$A = \frac{34.2\ Q}{\sqrt{h}} \tag{10}$$

where V = air velocity through regulator (feet per minute),
A = cross-sectional area of regulator (square feet),
h = static pressure drop at regulator opening (inches water gage),
q = air quantity through regulator (cubic feet per minute),
and Q = air quantity through regulator (cubic feet per minute in units of 100,000).

In equations 9 and 10, the assumptions used in the derivation of the classic regulator formula were eliminated. Instead, an overall discharge coefficient of 73 percent was determined experimentally for all pressure

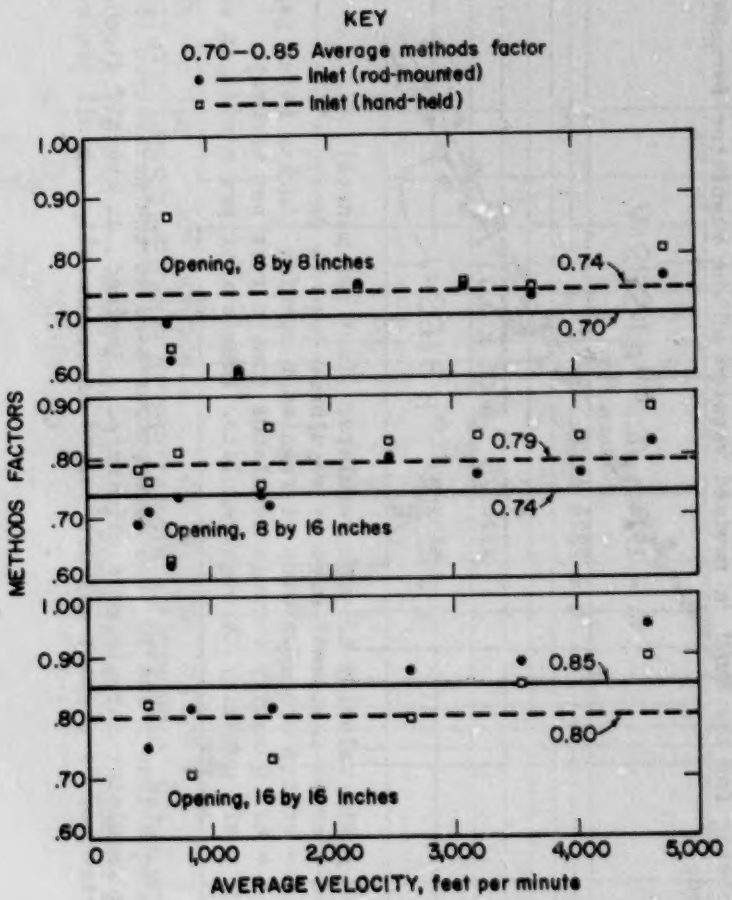

FIGURE 5. - Methods factors versus average velocity for 8- by 8-inch, 8- by 16-inch, and 16- by 16-inch opening sizes.

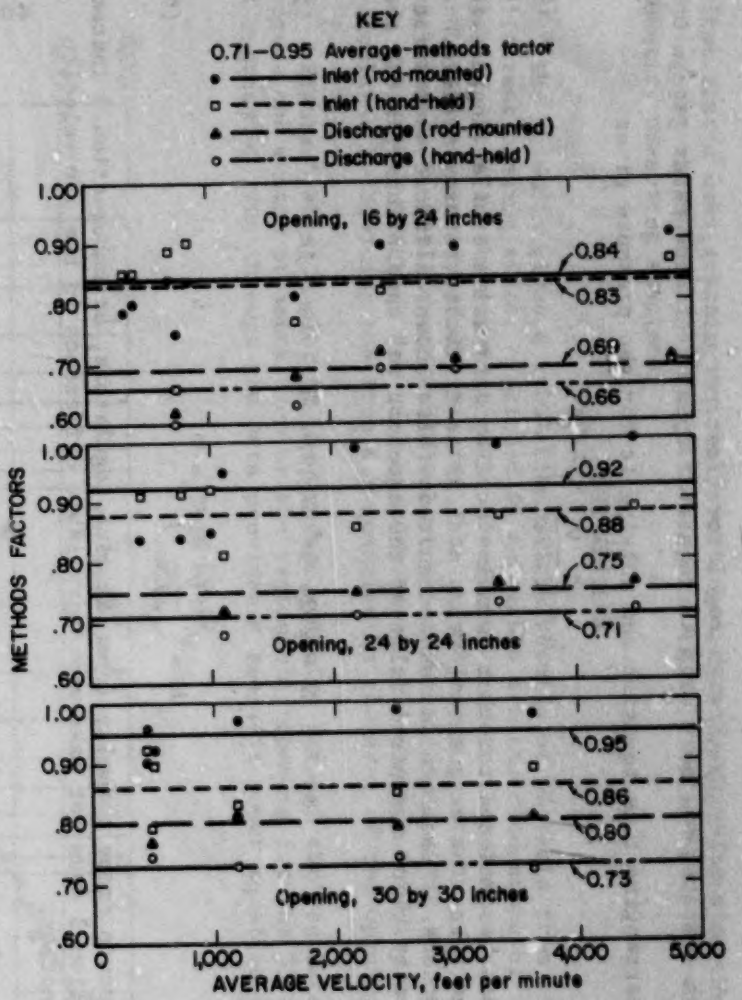

FIGURE 6. - Methods factors versus average velocity for 16- by 24-inch, 24- by 24-inch, and 30- by 30-inch opening sizes.

losses at the regulator. This was found by dividing the coefficient in equation 5 (2924) by the coefficient (4005) used to calculate the velocity from velocity pressure at standard air density, as follows:

$$\text{Overall Discharge Coefficient} = \frac{2924}{4005} = 0.73.$$

The second part of the data analysis involved the determination of methods factors that could be used to convert anemometer measurements at the centerline of the regulator to average air velocities passing through the regulator. Methods factors were determined by dividing the average air velocity passing through the rectangular opening by the centerline rotating vane anemometer velocity measurement. The average air velocity passing through the rectangular opening was determined by dividing the true air quantity determination by the area of the opening. Different factors were calculated for inlet and discharge readings and for rod-mounted and hand-held anemometer measurements.

The methods factors were plotted versus the average velocity for the rod-mounted and hand-held anemometer determinations on the inlet and discharge sides of the stopping for each of the eight different opening sizes tested. In general, the factor did not vary with velocity, but did vary with opening size, method of support, and location of reading. Figures 5, 6, and 7 show plots of these data (10).

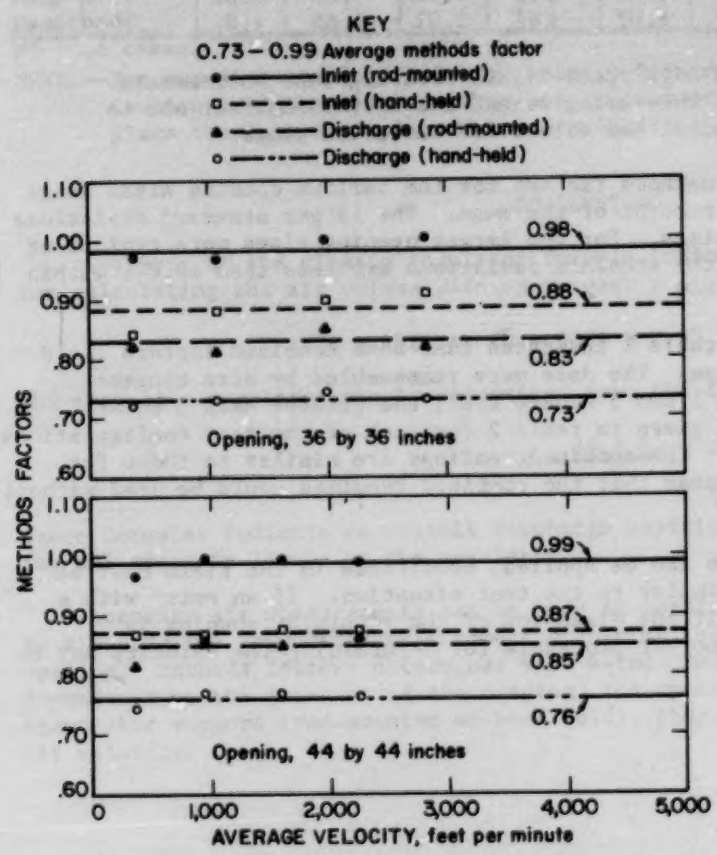

FIGURE 7. - Methods factors versus average velocity for 36- by 36-inch and 44- by 44-inch opening sizes.

Table 1 gives the average methods factors determined for each of the eight different opening sizes. Factors are given for inlet and discharge readings using either a rod-mounted or hand-held anemometer. The table also shows the nominal opening sizes, the actual opening areas, the range of velocities, and the standard deviation from the average methods factors for each set of tests (4). The average methods factors ranged from 0.70 to 0.99 for the rod-mounted inlet readings, from 0.74 to 0.88 for the hand-held inlet readings, from

0.69 to 0.85 for the rod-mounted discharge readings, and from 0.66 to 0.76 for the hand-held discharge readings. Rod-mounted and hand-held discharge readings for the three smallest opening sizes were not taken because the test setup did not facilitate taking measurements on the discharge side of the small openings.

TABLE 1. - Methods factors for centerline-corrected anemometer readings taken at rectangular openings of various sizes in 8-inch-thick stoppings

Nominal opening sizes, inches	Actual opening areas, square feet	Velocity range, feet per minute	Inlet				Discharge			
			Rod-mounted		Hand-held		Rod-mounted		Hand-held	
			Average methods factor	Standard deviation	Average methods factor	Standard deviation	Average methods factor	Standard deviation	Average methods factor	Standard deviation
8 x 8	0.41	670-4750	0.70	±0.06	0.74	±0.09	NT	--	NT	--
8 x 16	.85	415-4635	.74	±.06	.79	±.07	NT	--	NT	--
16 x 16	1.68	480-4585	.85	±.07	.80	±.07	NT	--	NT	--
16 x 24	2.56	320-4835	.84	±.05	.83	±.07	0.69	±0.04	0.66	±0.05
24 x 24	4.12	435-4480	.92	±.08	.88	±.04	.75	±.02	.71	±.02
30 x 30	6.39	465-3630	.95	±.03	.86	±.05	.80	±.02	.73	±.01
36 x 36	9.00	375-2835	.98	±.02	.88	±.03	.83	±.02	.73	±.01
44 x 44	13.18	375-2250	.99	±.02	.87	±.01	.85	±.02	.76	±.01

NT Not taken.

NOTE.--For use with standard and high speed 4-inch rotating vane anemometers. Caution must be exercised when using standard 8-vane anemometer not to place the instrument in airstream velocities above its range.

Standard deviations of the methods factors for the various opening sizes range from ±0.01 to ±0.09 within ±10 percent of the mean. The larger standard deviations occur with the smaller opening sizes. For the larger opening sizes more typical of the openings found underground, the standard deviations are less than ±0.04, within ±5 percent of the mean

Review of the test data in table 1 indicates that some combined factors could be derived to facilitate field use. The data were reassembled by size ranges: less than 1 square foot, between 1 and 3 square feet, and greater than 3 square feet. These average factors are given in table 2 for each of the test configurations. Since the standard deviations for the combined readings are similar to those for individual readings, it would appear that the combined readings could be used without losing accuracy.

Before these methods factors can be applied, conditions in the field must be judged to insure that they are similar to the test situation. If an entry with a large area is to be measured or if one dimension of the regulator opening is elongated to an extreme, then another procedure for determining the velocity may be required.

TABLE 2. - Combined average methods factors for centerline-corrected anemometer readings taken at rectangular openings of various sizes in 8-inch-thick stoppings

Nominal opening sizes, inches	Actual opening areas, square feet	Velocity range, feet per minute	Inlet				Discharge			
			Rod-mounted		Hand-held		Rod-mounted		Hand-held	
			Average methods factor	Standard deviation	Average methods factor	Standard deviation	Average methods factor	Standard deviation	Average methods factor	Standard deviation
8 x 8 and 8 x 16 Combined	Less than 1	415-4750	0.72	±0.06	0.77	±0.08	NT	--	NT	--
16 x 16 and 16 x 24 Combined	1 to 3	320-4835	.84	±.06	.82	±.07	0.69	+0.04	0.66	±0.05
24 x 24 through 44 x 44 Combined	Greater than 3	375-4480	.96	±.05	.87	±.04	.81	±.04	.74	±.02

NT Not taken.

NOTE.--For use with standard and high speed 4-inch rotating vane anemometers. Caution must be exercised when using standard 8-vane anemometer not to place the instrument in airstream velocities above its range.

CONCLUSIONS

Analysis of the classic regulator formula indicates that a more accurate formula for calculating the air volume passing through a mine regulator is:

$$q = 2924\ A\ \sqrt{h} = 4005 \times 0.73\ A\ \sqrt{h}.$$

The area of a regulator can be determined from the formula:

$$A = \frac{34.2\ Q}{\sqrt{h}}.$$

These formulas indicate an overall discharge coefficient of 73 percent accounting for all pressure losses at the regulator.

Accurate air measurements can be made at regulators by applying a methods factor to a centerline anemometer measurement either at the inlet or discharge side of the opening. Methods factors determined with 4-inch rotating vane anemometers showed a dependence on the location of the reading, the opening size, and the method of anemometer support (rod-mounted or hand-held); they showed little dependence on the air velocity.

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APPENDIX

TABLE A-1. - Results of 53 tests for eight different opening sizes

Nominal opening size, inches (ratio: opening area to tunnel area)	Actual opening areas, square feet	Air quantity, cubic feet per minute	Average computed velocity, feet per minute	Static pressure drop, inches water gage	Centerline-corrected velocities, measured with 4-inch rotating vane anemometers, feet per minute				Methods factors			
					Inlet		Discharge		Inlet		Discharge	
					Rod-mounted	Hand-held	Rod-mounted	Hand-held	Rod-mounted	Hand-held	Rod-mounted	Hand-held
8 x 8	0.444	298	671	0.053	976	776	NT	NT	0.69	0.86	NT	NT
(.01)	.404	280	693	.073	1,098	1,071	NT	NT	.63	.65	NT	NT
	.404	506	1,252	.240	2,038	2,074	NT	NT	.61	.60	NT	NT
	.404	905	2,240	.320	2,972	2,976	NT	NT	.75	.75	NT	NT
	.404	1,249	3,092	1.050	4,124	4,109	NT	NT	.75	.75	NT	NT
	.404	1,481	3,666	1.475	4,997	4,922	NT	NT	.73	.74	NT	NT
	.404	1,918	4,748	2.300	6,215	5,875	NT	NT	.76	.81	NT	NT
Mean-	.41								.70	.74		
Standard deviation-									±.06	±.09		
8 x 16	0.889	370	416	0.030	603	530	NT	NT	0.69	0.78	NT	NT
(.02)	.889	440	495	.037	699	650	NT	NT	.71	.76	NT	NT
	.889	659	741	.075	1,008	913	NT	NT	.74	.81	NT	NT
	.827	554	670	.075	1,094	1,092	NT	NT	.61	.61	NT	NT
	.827	1,177	1,423	.260	1,921	1,889	NT	NT	.74	.75	NT	NT
	.889	1,324	1,489	.300	2,060	1,755	NT	NT	.72	.85	NT	NT
	.827	2,050	2,479	.740	3,094	3,011	NT	NT	.80	.82	NT	NT
	.827	2,636	3,187	1.200	4,129	3,830	NT	NT	.77	.83	NT	NT
	.827	3,341	4,040	1.875	5,216	4,872	NT	NT	.77	.83	NT	NT
	.827	3,834	4,636	2.100	5,630	5,282	NT	NT	.82	.88	NT	NT
Mean-	.85								.74	.79		
Standard deviation-									±.06	±.07		
16 x 16	1.778	855	480	0.036	640	587	NT	NT	0.75	0.82	NT	NT
(.04)	1.655	1,397	844	.095	1,036	1,194	NT	NT	.81	.71	NT	NT
	1.655	2,509	1,516	.300	1,858	2,080	NT	NT	.82	.73	NT	NT
	1.655	4,373	2,642	.870	3,019	3,327	NT	NT	.88	.79	NT	NT
	1.655	5,887	3,557	1.625	4,009	4,190	NT	NT	.89	.85	NT	NT
	1.655	7,590	4,586	2.350	4,815	5,115	NT	NT	.95	.90	NT	NT
Mean-	1.68								.85	.80		
Standard deviation-									±.07	±.07		
16 x 24	2.667	856	321	0.017	409	378	NT	NT	0.79	0.85	NT	NT
(.06)	2.667	1,063	399	.021	500	471	NT	NT	.80	.85	NT	NT
	2.667	1,825	684	.062	816	771	NT	NT	.84	.89	NT	NT
	2.482	1,847	744	.090	989	1,119	1,202	1,252	.75	.66	0.62	0.59
	2.667	2,289	858	.100	1,028	956	NT	NT	.84	.90	NT	NT
	2.482	4,253	1,714	.395	2,107	2,219	2,520	2,711	.81	.77	.68	.63
	2.482	6,019	2,425	.740	2,716	2,952	3,365	3,512	.89	.82	.72	.69
	2.482	7,577	3,053	1.200	3,431	3,670	4,327	4,433	.89	.83	.71	.69
	2.482	11,997	4,834	2.950	5,301	5,534	6,816	6,887	.91	.87	.71	.70
Mean-	2.56								.84	.83	.69	.66
Standard deviation-									±.05	±.07	±.04	±.05
24 x 24	4.0	1,749	437	0.032	521	479	NT	NT	0.84	0.91	NT	NT
(.10)	4.0	3,045	761	.090	906	834	NT	NT	.84	.91	NT	NT
	4.0	4,037	1,009	.135	1,186	1,097	NT	NT	.85	.92	NT	NT
	4.211	4,597	1,092	.160	1,149	1,348	1,514	1,609	.95	.81	0.72	0.68
	4.211	9,237	2,194	.590	2,217	2,567	2,931	3,099	.99	.85	.75	.71
	4.211	14,169	3,365	1.450	3,410	3,860	4,412	4,598	.99	.87	.76	.73
	4.211	18,867	4,480	2.400	4,486	5,060	5,871	6,223	1.00	.89	.76	.72
Mean-	4.12								.92	.88	.75	.71
Standard deviation-									±.08	±.04	±.02	±.02
30 x 30	6.25	2,895	463	0.021	513	501	NT	NT	0.90	0.92	NT	NT
(.16)	6.25	3,197	512	.028	555	572	NT	NT	.92	.90	NT	NT
	6.46	3,087	478	.030	499	602	620	639	.96	.79	0.77	0.74
	6.46	7,797	1,207	.160	1,238	1,458	1,483	1,654	.97	.83	.81	.73
	6.46	16,236	2,513	.720	2,546	2,952	3,171	3,384	.99	.85	.79	.74
	6.46	23,442	3,629	1.550	3,720	4,097	4,486	5,047	.98	.89	.81	.72
Mean-	6.39								.95	.86	.80	.73
Standard deviation-									±.03	±.05	±.02	±.01
36 x 36	9.0	3,356	373	0.020	385	444	455	516	0.97	0.84	0.82	0.72
(.23)	9.0	9,705	1,078	.120	1,117	1,229	1,331	1,472	.96	.88	.82	.73
	9.0	17,949	1,994	.430	1,998	2,211	2,344	2,677	1.00	.90	.85	.74
	9.0	25,494	2,833	.890	2,822	3,131	3,445	3,860	1.00	.90	.82	.73
Mean-	9.0								.98	.88	.83	.73
Standard deviation-									±.02	±.03	±.02	±.01
44 x 44	13.178	4,940	375	0.020	389	436	460	504	0.96	0.86	0.82	0.74
(.33)	13.178	12,423	943	.095	943	1,084	1,095	1,225	1.00	.87	.86	.77
	13.178	20,967	1,591	.270	1,600	1,815	1,867	2,060	.99	.88	.85	.77
	13.178	29,622	2,248	.480	2,257	2,572	2,591	2,935	1.00	.87	.87	.77
Mean-	13.18								.99	.87	.85	.76
Standard deviation-									±.02	±.01	±.02	±.01

NT Not taken.

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